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# PYTHON–SIMULINK CO-SIMULATION OF DC-COUPLED PV–PEM ELECTROLYZER SYSTEMS UNDER MINUTE-LEVEL SOLAR VARIABILITY

Direct coupling of photovoltaic (PV) systems with Proton Exchange Membrane (PEM) electrolyzers offers a simplified pathway for renewable hydrogen production but remains sensitive to solar variability and operating-point mismatch. This work presents a Python–MATLAB/Simulink co-simulation framework to evaluate direct and indirect PV–PEM coupling architectures under minute-level solar irradiance. High-resolution inputs enable the detailed resolution of PEM electrochemical dynamics, including transient voltage and current density behavior that is not observable with hourly data. Five system configurations are assessed, ranging from conventional indirect coupling to reconfigurable direct PV–PEM architectures with optional battery integration. Results show that Python-based reconfiguration significantly reduces mismatch losses in direct coupling schemes, narrowing the performance gap with indirect solutions. The modular Simulink-based framework enables straightforward substitution of PV models, converter topologies, control, and system architectures, providing a flexible and practical tool for assessing advanced PV–PEM concepts under realistic operating conditions.

*Keywords: Photovoltaic systems, PEM electrolyzer, Coupling Simulation, Solar-to-hydrogen, Minute-level irradiance, System reconfiguration*

*Field of application for the findings: Renewable hydrogen production, power-to-hydrogen systems, PV–electrolyzer integration, energy system modeling, and control.*

*Addressed audience: Researchers and engineers in solar energy, hydrogen technologies, power electronics, and energy system modeling, as well as system designers and policymakers.*

## 1. Introduction

The integration of PV power with PEM water electrolysis typically relies on either indirect or direct coupling. Indirect coupling utilizes DC-DC power converters equipped with maximum power point tracking (MPPT) to actively align the PV output with the electrolyzer load. Recent studies have deeply investigated these indirect systems to optimize control and understand transient behaviors. For instance, Lin et al. (Lin et al., 2025) constructed a combined PV-Battery-PEMWE model to analyze how the electrolyzer reacts to fluctuating loads. They found that operating the system at a constant current (galvanostatic mode) causes the voltage to adjust in multiple distinct stages, whereas operating at a constant voltage (potentiostatic mode) leads to temporary spikes, or overshoots, in current. Similarly, Renaudineau et al. (Renaudineau et al., 2025) performed optimal sizing for off-grid PV-PEM systems using DC-DC converters, emphasizing the importance of using high-resolution, 1-minute environmental data to accurately capture solar variability. While indirect coupling ensures optimal power matching, the DC-DC converters introduce persistent switching and conduction losses, increase system complexity, and raise capital costs.

To circumvent power electronic losses, direct coupling connects the PV array straight to the electrolyzer. Weng et al. (Weng et al., 2026) experimentally and numerically investigated a directly coupled PV-PEM system, demonstrating its feasibility but highlighting a major drawback: system efficiency is severely constrained by the fixed electrical characteristics of the PV array. Because solar irradiance constantly fluctuates, the fixed PV array frequently operates far from its maximum power point, causing significant mismatch losses and a bimodal drop in efficiency under off-design conditions. To address this mismatch without relying on standard converters, Geng et al. (Geng et al., 2025) optimized the exact number of series-connected electrolytic cells, finding that a specific configuration provided better stability under fluctuating irradiance. However, static sizing alone cannot dynamically adapt to daily and seasonal weather changes.

To overcome the severe energy mismatch that occurs when solar panels and electrolyzers are directly connected without converters, researchers are exploring two main strategies: incorporating passive energy buffers, such as a battery directly wired into the system without electronic controllers to naturally stabilize power, or dynamically changing the physical wiring configuration of the solar panels. Astakhov et al. (Astakhov et al., 2021) investigated the integration of a battery in a directly coupled parallel configuration without any power management electronics. Their theoretical and experimental results demonstrated that the battery effectively buffers short-term solar fluctuations, spreads energy delivery over the diurnal cycle, and reduces the kinetic overpotential losses in the electrochemical cell by softening rapid current spikes. Another emerging solution is the dynamic reconfiguration of the PV source itself. Di Caro and Vitale (Di Caro & Vitale, 2024) proposed enhancing direct-coupled PEM systems by actively altering the electrical connections (parallel arrays) of the PV source via static switches based on incoming solar radiation. Their graphical and static analysis showed that adjusting the PV array configuration under medium and low irradiance conditions dramatically improved matching, leading to a 17% to 93% increase in delivered energy compared to a fixed PV architecture.

While the literature demonstrates the immense potential of PV array reconfiguration and the necessity of high-resolution meteorological data, a significant research gap remains. Existing studies on reconfigurable direct-coupled systems largely rely on static models, hourly sampled data, or graphical approaches, which fail to capture the true transient dynamics of the system. Conversely, studies that model electrochemical transient behaviors and use minute-level data typically focus only on standard indirect coupling with DC-DC converters. Consequently, the performance of directly coupled PV-PEM systems under high-resolution solar variability, realistic electrical dynamics, and dynamic structural reconfiguration remains insufficiently understood, particularly regarding the transient electrochemical response of the PEM stack to rapid operating-point shifts. To bridge this gap, this work presents a high-fidelity Python–MATLAB/Simulink co-simulation framework to systematically evaluate direct and indirect PV–PEM coupling architectures under minute-level solar irradiance. Unlike previous models, this approach explicitly resolves the fast transient effects on PEM operating voltage, current density, and efficiency that are completely unobservable with hourly inputs. By employing a Python-based reconfiguration algorithm that dynamically adjusts the system configuration in real-time, this work provides a practical platform to demonstrate how active reconfiguration can substantially mitigate mismatch losses in direct coupling schemes, while simultaneously enforcing strict electrical feasibility and electrochemical constraints via Simulink.

## 2. Methodology

Direct coupling of PV systems with PEM electrolyzers is an attractive pathway for renewable hydrogen production, as it reduces system complexity by avoiding grid interaction and extensive power-electronic conversion. However, the performance of directly coupled PV–PEM systems under high-resolution solar variability, realistic electrical dynamics, and different coupling architectures remains insufficiently understood, particularly with respect to the electrochemical response of the PEM stack.

This work presents a high-fidelity Python–MATLAB/Simulink co-simulation framework to systematically evaluate direct and indirect PV–PEM coupling architectures under minute-level solar irradiance. MATLAB/Simulink is used to model detailed PV, power-electronic, and PEM electrolyzer electrical and electrochemical dynamics, while a Python-based reconfiguration algorithm actively adapts system operating conditions in selected architectures. Minute-level irradiance profiles, obtained via downscaling of hourly data, are employed to capture short-term solar variability. Unlike steady-state hourly models, this high resolution allows the simulation to capture the dynamic electrical interactions between the PV source, the specific coupling architecture, and the PEM cell. Because each architecture responds differently to rapid irradiance shifts, for example, indirect systems experience MPPT tracking delays, while direct systems face instantaneous operating-point shifts that trigger the PEM cell's voltage ramping (due to electrical double-layer capacitance) and thermal inertia, minute-level data is critical for accurately predicting the unique mismatch losses and real-world hydrogen yield of each specific configuration.

Five system configurations are investigated: (i) direct PV–PEM coupling without active reconfiguration, (ii) direct PV–PEM coupling with Python-based reconfigurable control, (iii) indirect PV–PEM coupling via DC–DC power electronics, (iv) indirect PV–PEM–battery coupling, and (v) direct PV–PEM coupling with Python-based reconfiguration and an indirectly connected battery as suggested by our previous work. In reconfigurable direct architecture, the Python algorithm dynamically adjusts system configuration to improve current and power matching without relying on grid interaction or conventional power converters, while Simulink enforces electrical feasibility and electrochemical constraints. System performance is evaluated in terms of hydrogen yield, solar-to-hydrogen efficiency, and efficiency losses associated with mismatch, transients, and rapid operating-point shifts.

## 3. Preliminary Results

Analyzing the system's dynamic response (Figure 1) revealed that the severity of these fast transients is highly dependent on the coupling architecture. During rapid irradiance shifts in the minute-level data, the equivalent circuit model captured transient voltage overshoots of up to 0.3 V per cell and rapid operating-point shifts that resulted in temporary efficiency drops of up to 10%. Crucially, these efficiency drops were not uniform across all simulated cases. Architecture utilizing direct coupling or active reconfiguration experienced more severe electrochemical lags compared to actively buffered indirect systems. Traditional hourly models fail to capture these architecture-specific differences, which are essential for calculating the true energy efficiency.

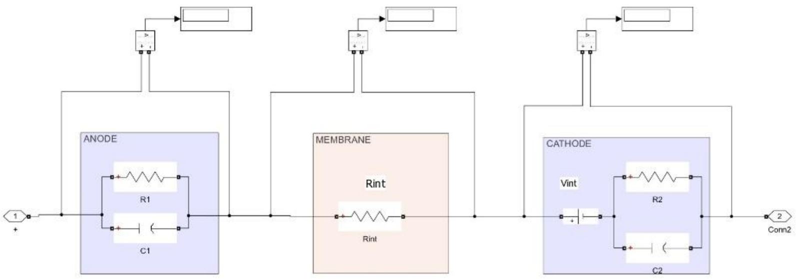


**Figure 1: PEM electrical circuit**

Initial simulations across the evaluated architectures indicate significant variations in system efficiency and hydrogen yield under minute-level solar variability. The baseline direct PV–PEM coupling (Configuration i) exhibited severe mismatch losses, particularly during low irradiance periods, resulting in a baseline solar-to-hydrogen efficiency of 10%. Implementation of the Python-based reconfiguration algorithm (Configuration ii, shown in Figure 2) actively mitigated these issues. By dynamically adjusting the parallel stack configuration in response to real-time PV power generation, the Python script reduced electrical mismatch losses compared to the baseline. This active optimization increased the overall StH efficiency to 14 %, successfully narrowing the performance gap with the traditional indirect architecture (Configuration iii, Figure 3) when advanced power electronics are used.

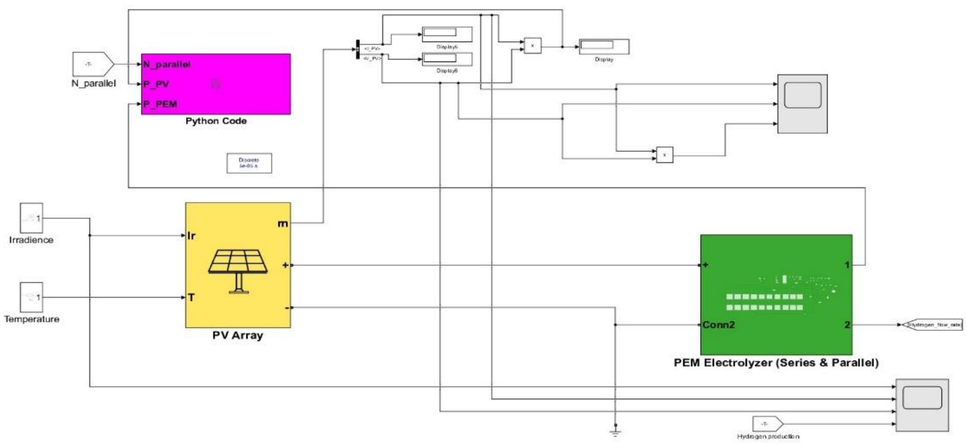


**Figure 2: Python- Matlab/Simulation co-simulation for direct coupling**

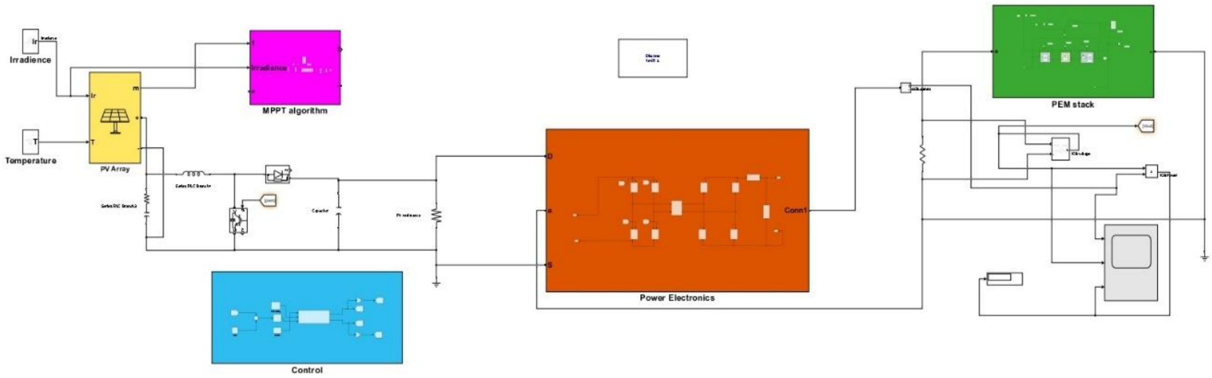


**Figure 3: Indirect coupling with DC/DC converter**

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